IV

SCIENCE IN THE HISTORY OF CIVILIZATION

IN THIS title the only word which does not give any serious difficulty to a scientist is "History." But he is really uneasy about the two others, "Science" and "Civilization." Fortunately, if one of the principles of what we shall call good thinking is the formation of good definitions, the scientist, or at least the mathematician, solves his problem by choosing them, logically speaking, arbitrarily. And if somebody dares to ask him, "Why this definition?" he has the right to answer—and generally uses this right, as he does in a freshman class when interrupted by a "Why?" after having begun, "Let *a* be positive"—"Because I desire it!"

It would be relatively easy to find a suitable definition for each of the two words separately. The difficulty arises from the fact that both occur in the same title. One cannot hope that the auditor will forget the given definition of "Civilization" when that of "Science" is being proposed. These two notions are so related that it would be most agreeable to give to Science a meaning so large, and to Civilization a sense so strict, that the lecture would be over after having merely suggested that, by definition, they constitute the same thing.

It is difficult to give a definition of our entities without reducing these words to others perhaps more difficult to define; we shall instead, contrary to all mathematical rules, appeal to the imagination and to concrete experience.

In a French dictionary which is generally considered a good one, we find: "Civilization—action of civilizing. Antithesis—Barbarism"; and, "To civilize—to refine customs." Of course the dictionary makes here a fundamental mistake; or, if you prefer, we do not want this definition. This mistake could be compared in physics to a confusion between "potential" and "difference of potentials." Civilization corresponds to the second of these two notions and not the first. The antithesis of civilization is not barbarism. Civilization is what has been added to barbarism in order to obtain its antithesis. This has more than a philological significance. This interpretation shows better the dynamical nature which characterizes a true civilization. Not only is a stagnant state of things contrary to the notion we have of civilization, but even a uniform speed is not enough. A positive acceleration is necessary. If the members of a community live and think as they lived and thought fifty years ago without having added new ideas, or without having had new expressions of art or new ways of understanding social life, we shall not say that that community is civilized.

The word science is taken here in its typical English and French meanings: it means, in other words, "natural science," and not mere knowledge. The German word "Wissenschaft" has a larger and thus a less precise meaning. We shall therefore exclude history, social sciences, philology, and humanities in general, not because we do not consider them as an important part of human knowledge, but because the vague notion of "natural" we have in our mind excludes this kind of activities. Mathematics does constitute a natural science, not only because modern physics, chemistry, and other branches of typically *natural* sciences could not live without mathematical speculation, but because even the most abstract parts of mathematics as, for instance, topology, theory of groups, and others involve relationships between entities which, although created *a priori*, represent abstract forms disengaged from Nature; at any rate, the relations between them symbolize relations between natural forms. If we recall that, after all, each science bases its conclusions, by necessity, only on a finite number of facts concerning the subject studied, we see that abstraction of an object is proper to a science. Mathematics thus must be considered, from this point of view, as the image of all sciences. We do not try to prove that mathematics is the Queen of Sciences—even though we think so! On the contrary, we try only to make you agree that mathematics is a full Citizen of the Kingdom of Science.

Science and applications of science constitute one—we should rather say two—of the components of our civilization. We shall give much more time to pure than to applied science. It is not that we have any contempt for the latter: we agree, of course, that the material achievements due to science constitute one of the terms of the difference, "Antithesis of Barbarism minus Barbarism." It happens that the purpose of this talk, as we understand it, is to compare creative, disinterested knowledge with two or three other activities of human intellect. On the other hand, two striking facts make it possible to assert that applied science, from the point of view of its influence on the intellect's desire to understand the world, or its place in the world, plays only a secondary rôle. First, true as it is that Science at the beginning followed its own applications, the technical applications which follow Science are relatively very recent. It would be difficult to find technical commodities resulting from scientific discoveries, and historically following these discoveries, realized more than two centuries ago. But science did exist in many different eras preceding this epoch. Second, since the era of great modern discoveries began, only a very small part of the new knowledge has been applied. By far the most profound applications of Newton's ideas in mechanics have been made in astronomy, that is to say, in pure science itself, and not in technical achievements.

We shall not try to enumerate the different terms of what constitutes human progress; but let us, besides science, recall the most striking intellectual activities: religion, philosophy, arts. . . . In order to show the importance of science we could try to use a famous method used by mathematicians in order to prove the independence, with respect to one another, of different postulates which form an Axiomatic. One then tries to form axiomatics in which some postulates hold without the others being true.

It seems that Thibet is a good example of a country where only religion has been developed to a high degree; where a subtle theology is and has been for centuries the center of thought of a whole people, but where science is nonexistent; where art is, in comparison with religious achievements, poor; and where philosophy is entirely absorbed by theology.

There is also the prehistoric example of a community—nobody in our day is able to say how far this expression may be applied in those circumstances—a community where genuinely inspired art (painting) was probably the only manifestation of the intellect. We have in mind the Cro-Magnon man. His wall-paintings were, by their vivacity and inspiration, infinitely higher than the much later artistic expression of the Egyptians. Certainly no science troubled the brain of this ancient ancestor of European races; religion, on the other hand, was certainly reduced to magic rites and should not be envisaged as a product of intellectual activity.

But neither the ancient or modern Thibetans, nor the Cro-Magnon men could be considered as furnishing an example of something even similar to what we should like to call civilization, if we take as prototypes of civilization that of ancient Greece, or that of the Renaissance, or that of our modern countries. In both cases, Thibetan and Cro-Magnon, science is totally absent. That is perhaps the point which makes the big difference. Of course a more rigorous evaluation of the importance of science as an element of civilization could be furnished if only it were possible to find and to study a community where science is the only intellectual activity. Perhaps an interesting example would be the comparison, from that specific point of view, between Czarist Russia and Russia of our day. The "homo sovieticus," as some writers call the members of the numerous states of the U.S.S.R., has, it seems, great admiration for sciences, though the expression of other intellectual activities is considerably reduced. But the Russian experiment seems to be too young to furnish a decisive proof of any proposition concerning the importance of science when other elements are missing.

In studying the total expansion of human intelligence, the French philosopher Auguste Comte thought that he had discovered the fundamental law that each of our principal conceptions, every branch of our knowledge, passes successively through three different theoretical states: theological, metaphysical, and scientific.

In Comte's mind the latest state, the scientific or positivistic state as he calls it, is the highest achievement of the human mind as far as the perception of the external world is concerned. We do not accept the philosophy of Comte since we believe that the three theoretical states mentioned correspond to three different and independent states of our mind; and we meet every day men who, in different moments of their lives, we should even say in different hours of each day, are under the influence of one of these states of mind. For these individuals none of the three states is subject to the others. But it is impossible not to accept Comte's law as a historical principle. It seems obvious that at the beginning the human spirit tried to determine the intimate nature of things, the first or last reason of phenomena. This was the theological state. Then man, or at least the professional thinker, tried to replace the supernatural causes by abstract forces or abstract matters to which he gave different names; this is the metaphysical state. And only at the last stage did he try to formulate statements of physical laws based on experiments or did he try to idealize some of nature's laws. This is the scientific state.

Only in modern times have the rights and the fields of investigation of each of these three branches of human intelligence been delimited. It happened and it still happens that each one of these branches overlaps the neighbors' fields of activities, but essentially they are independent.

Hence until our recent epoch the history of human intelligence is a periodic function of time; every period, as far as the desire for the understanding of natural phenomena is concerned, is itself a succession of three different eras: theological, metaphysical, scientific.

Writers attribute the honor of creation of disinterested, rational sciences to the Greeks. As a matter of fact, the ancient physicists of the Ionian School, such as Thales of Miletus (640–598 B.C.), author of a famous cosmology where water played the fundamental rôle; Anaximander (610–597 B.C.), for whom the eternal substance was the basis of things; and Anaximenes (?–480 B.C.), for whom air was the great principle—all these physicists, in their metaphysical speculations, achieved the "laicization" of ancient oriental religions, principally those of Chaldea and Egypt.

But these same Masters of the Ionian School were perhaps the first men to lay down a bridge between metaphysics and pure science. Thales originated, starting from empirical rules, the science of deductive geometry; he was able to predict an eclipse. Anaximander observed the revolution of the heavens with the pole star as center, and understood the existence of the other half of the heavenly sphere.

It seems that in Pythagoras (582-aft. 507 B.C.) and his School the three fundamental tendencies, described above, met. If he came back to mysticism—a mysticism based on the knowledge of numbers—he also experimented with sound and gave deductive proofs for geometrical theorems. It seems that he already knew the material of the first two books of Euclid. At any rate, he gave a real proof of the famous theorem, bearing his name, on right-angled triangles.

But certainly the most learned man of Greek Antiquity, the man who gave the greatest number of systematic theories in scientific fields already available, or introduced by himself, was Aristotle (384–322 B.C.).

His general ideas were of course too often wrong. For instance, contrary to Plato who had foreseen inertia, Aristotle asserted that an acting cause was necessary at every moment in order to keep a body moving. But he had ideas on planets, comets, and meteors. He was the first, in his *Meteorologics*, to treat chemical questions. He gave, for instance, ideas—of course false—on the origin of metals and minerals and on properties of composite bodies. In biology he used direct observation and inquiry on different animals. He used dissection and vivisection.

Aristotle's ideas in physics were particularly wrong, and the admiration and authority by which his name was surrounded during many centuries—and which were so merited by the genius of his daring spirit, if not by the actual discoveries—constituted one of the most formidable obstacles in the expansion of mankind's thought. The earth, though spherical, was the center of the universe. In a vacuum the speed of fall would be the same for all bodies, but, argued Aristotle, this is obviously impossible. Thus follows the impossibility of a vacuum. He refused to believe in the atomistic theory already introduced and developed by Leucippus (5th cent. B.C.) and Democritus (460?–362? B.C.).

Feeling the necessity of experiments for the formulation of natural laws, Aristotle was still slave of the metaphysical desires of his time. He needed, if not "fundamental elements," at least "principal qualities"—hot and cold, wet and dry.

Aristotle's greatest discovery was probably that of formal logic, in forms which are acceptable, almost without variations, to the modern mind. He created thus the principle of rigorous proof. Certainly science would be impossible without the inductive method. But it would also be impossible without the deductive method. This method became rigorous because based on sure principles of Aristotelian logic. It is true that a modern scientist need not use rules of formal logic: he is logical (when he is!), as a result of his general education almost by atavism; but this education—this, let us say, artificial atavism—is largely due to the influence of Aristotle's logic on the Greeks who followed him directly.

The principal fault of the thinkers of the Middle Ages was that they started from false assumptions and made false theories by means of rigorous, formal logic. Often the false assumptions were introduced by the help of a little swindle—they were necessary for the proof of things conceived very much *a priori*.

The first true scientist of the Hellenic world, that is to say the man who was absolutely free from any metaphysical ambition, the man who did not try to find the leading element or the universal force, but who sought in experiments as well as in facts the explanation of other facts, was Archimedes (287?–212 B.C.). He personifies the third link of the first chain in history of human thought, the chain: theology, metaphysics, science.

Archimedes measured the circumference of a circle by methods which may be regarded as forerunners of the modern methods based on the notion of limits—he found the ratio of the circumference to the diameter to be a quantity of about $3\frac{1}{7}$. He found also the ratio of the volume of a cylinder to that of a sphere inscribed in it.

Archimedes was the creator of mechanics and hydrostatics. He was the first to introduce a clear idea of relative densities of bodies. Everybody knows the famous law of Archimedes concerning bodies immersed in a liquid. Archimedes announced the theoretical principle of the lever.

For the first time in human history scientific principles were applied conscientiously: let us recall hydraulic screws, burning mirrors, the pulley. . . . This is perhaps the right moment to recall that Archimedes used his genius to defend his city; for three years, thanks to his scientific advices, Syracuse could hold out against the powerful Romans.

The French thinker Ernest Renan used to speak about the Greek Miracle. We should not consider as a miracle, as Renan did, the fact that the Greeks were the first to think rationally and abstractedly: that is to say, in a way not immediately related to applications. But there was a miracle in the passage, *without any organized opposition*, from the theological to the metaphysical stage and then to the scientific. Such passages became very difficult and dangerous in later centuries. They were then accomplished in the midst of revolutions, not always bloody, it is true.

It seems that with the end of the civilization of the Ancient Greeks, and that of their Roman disciples (in science they were almost mere imitators), there ends for a certain period the free evolution of human thought.

Creative minds always were few; they were, indeed, much fewer before the invention of printing and the organization of popular school systems, because only a few had any chance to think. But with the birth of a new religion and a new morality, the few great minds were all fascinated by the creation of a new philosophy. No room was left for things which were not directly related to religious thought.

When some centuries later the heirs of the first great theologians tried to have some ideas on nature, the Greek science had been forgotten and the human mind had lost its freedom. This freedom was lost in two different ways. The human mind was imprisoned by the limited means and fields of thought; it was also limited by a new fanaticism which made free thinking a very dangerous enterprise.

We shall make a leap over the Dark Ages, although this epoch saw the glory of Arabic science. We shall also omit the beginning of the Middle Ages with its rich expansion of Scholasticism.

It was during the most brilliant epoch of Scholastic Philosophy, personified by Thomas Aquinas (1225?–1274), that there appeared one of the purest precursors of the new scientific thought—Roger Bacon (1214?–1294). He was a great precursor, perhaps not so much by his real scientific achievements as by his scientific philosophy.

Bacon studied at Oxford under Lord Robert Grosseteste, Bishop of Lincoln, and Adam Marsh. Universities were organized at that time in almost all important countries of Europe. The University of Bologna, in Italy, was created about the year 1000. The Sorbonne was founded only in 1253, but a school of dialectics was organized in Paris as early as the beginning of the twelfth century and its constitution was adopted by Oxford and Cambridge. Lord Robert, Chancellor of Oxford, was very learned; as Bacon puts it, "Lord Robert and Friar Adam Marsh were perfect in all knowledge." Bacon was thus educated in an atmosphere of knowledge, if not science.

But here is exactly Bacon's great contribution: he was not satisfied with "knowledge," that is to say with reading of Greek and Arabic authors. "The admirable Doctor," as Bacon used to be called, was the first man of the Christian Era who understood the importance of experiment. Certainty, he tried to prove, comes only after experience. Friar Bacon (he was a Franciscan) did not have an easy life. He had many ideas; he had also wealth which he was willing to spend for his personal research work, but his Order gave him a great amount of trouble. Fortunately for him, and for us, Pope Clement IV solved some of his difficulties in ordering him to write up his work.

We do not know whether we diminish or increase Bacon's fame in saying that it is probably not true, as some believe, that he invented gunpowder. But he did know the magnet and burning glasses; he described a telescope. He knew Arabic mathematics, which was mostly concerned with astrology. What is more important, he understood the significance of mathematics both as a tool for experimental research and as an influence on the qualities of the human mind. From that point of view he would have been a good educator even in our day.

Of course Bacon was not free of the mysticism of his time. But it can be said that Bacon constitutes a new Miracle—we do not speak in the name of his contemporaries! Unfortunately Bacon was too much of an isolated phenomenon in those times to have had any real influence on his immediate successors. We must wait for more than two centuries, as a matter of fact until the Renaissance, in order to find another great and free mind. The name of the new colossus was Leonardo da Vinci.

Leonardo da Vinci (1452–1519) is perhaps better known to the world as painter, sculptor, and architect, but he was also a great physicist and biologist. No authority, neither that of Scholastic thinkers nor that of Aristotle, was strong enough to influence his powerfully original mind. He was perhaps also the first man of the Renaissance not to involve theology in the study of natural phenomena. We do not know whether Leonardo was acquainted with Bacon's work. But for him, too, experience was the only proof of reality. He, too, understood the spirit and importance of mathematics. He understood its abstract nature, but also its possibilities for application in the study of a set of experiments. It is significant that he was particularly interested in Archimedes' work. And from many points of view he was the Archimedes of his time.

A great number of principles which form the basis of rational mechanics were familiar to Leonardo da Vinci. It should be said that he was very much the engineer. He illustrates perfectly well the case where a man is a physicist because he is an engineer, and not an engineer because a physicist. He seems to have known the existence of acceleration during the fall of a body. He gave proofs of the law of the lever. He had very clear, if not very true, astronomical ideas. Leonardo da Vinci remarked that liquids in communicating vessels stand at the same level. He studied the laws of sound and remarked the analogies between the propagation of sound and that of light. He discovered important laws in hydrodynamics.

Leonardo da Vinci was perhaps the first Christian to dissect the human body, and this allowed him to make very accurate anatomical drawings. He knew the functions of the heart. Some think that he knew the circulation of the blood perhaps as well as Harvey did later.

He did not believe in astrology and alchemy. Unfortunately Leonardo da Vinci never published his notes, which were discovered much later, but he was in touch with many great thinkers of his time and thus participated in the expansion of clear and new ideas.

The great astronomical revolution—we might have said the great revolution in human thinking—was brought about by Nicolas Copernicus (Nicolaus Koppernigk) (1473–1543), Polish astronomer and mathematician.

Ptolemy's geocentric theory satisfied almost everybody; it had the authority of Aristotle; it had also the blessings of the great scholastic philosopher Thomas Aquinas, who reigned over all educated minds of the Middle Ages. Theology and philosophy accepted this theory willingly, since it placed the center and the reason of creation—man—in the center of the world. It is true that the mathematical apparatus on which Ptolemy's conception depended was rather heavy, since a whole sky had to move round the Earth. And disciples of the Pythagorean School (who became numerous through the influence of Neo-Platonism, and especially of Saint Augustine's writings) were rather shocked by this lack of harmony. Let us not forget that everything had to be, in the minds of Pythagoreans, mathematically simple. Copernicus' theory had this advantage.

Above all a fixed sky with fixed stars. In the center of this sphere the sun. The farthest moving body is Saturn, which revolves round the sun in thirty years; then comes Jupiter, completing its revolution in twelve years; next Mars, in two years. The Earth comes afterward (revolving in one year, by definition!); then come Venus (nine months) and Mercury (eighty days). Every planet spins on its axis. The trajectories were of course circles. Copernicus was satisfied with his own theory because of its harmony.

Many objections of even a scientific order were made to Copernicus' theory. If the earth revolves round its axis, why does not a body thrown upward fall to the west of its point of projection? Would not the earth, if Copernicus' theory were true, disintegrate? But Copernicus replied that a revolving sky with a fixed earth would do so even more.

Giordano Bruno (1548–1600) went even further: he dared to abandon even the idea that the stars were fixed, and believed, as we do nowadays, that they are scattered through infinite space. This was too much for his time. He was burned at the stake in 1600.

Until the sixteenth century there were only isolated periods in which epoch-making discoveries were conceived or during which science was advancing. In between two such intervals, not only science—physics, astronomy, mathematics—did not make any progress, but often known principles were forgotten. These progress-making time-intervals, in which sporadic expressions of human genius evolved, appeared more and more often. But if we try to go backwards from our times through streams of continuous progress, we should certainly be obliged to stop, at the end of the sixteenth century, or otherwise be obliged to make a great leap in order to meet Copernicus, almost a century earlier.

It seems, indeed, that the last great continuous interval—we have in mind continuity with respect to time—in which positive progress has been made, and which continues through our day, began with such men as Tycho Brahe, Kepler, Galileo. If we are looking for more than continuity in time; if we desire to establish a continuous path in our scientific way of thinking; if we want, still in retrospect, not to be obliged to meet a kind of thinking almost inconceivable for scientific minds of the latest centuries, we should stop with the last of these three men: Galileo.

Here are the three astronomical laws of Kepler based on observations of Tycho Brahe: "(1) The trajectories of planets are ellipses with the sun in one focus, (2) the area swept inside such a trajectory by the straight line joining the center of the planet to the center of the sun is proportional to the time, (3) the squares of the periodic times which the different planets take to describe their trajectories are proportional to the cubes of their mean distances from the sun." These three laws constitute an important part of the sum total of human knowledge. And the astronomical achievements of many years which followed directly Kepler's epoch were based on his discoveries.

But the spirit which guided Kepler in his research was still of Pythagorean type—the nostalgia for the greatest geometrical harmony in the world. Fortunately, in its first approximation the truth about nature is harmonious; or it would be truer to say that we call harmony one of the properties of an idealized, simplified (too often over-simplified) world.

Galileo no longer cared for finding first or ultimate causes. As a matter of fact he did not care for causes, that is reasons, at all. He wanted only to know how things happen; he wanted merely to describe phenomena. This is also the modern point of view. When a physicist or an astronomer gives a mathematical theory of a set of happenings, he does not try to explain all of them; he merely explains some of them by some others. Mathematics serves only to make these transitions, or to describe the ways in which the phenomena which serve to explain the other phenomena occur. A scientific theory does not leave the field of phenomena or the field of their idealizations: that is to say, their mental simplification.

This principle is one of the most important axioms of our scientific civilization. It makes the difference between a professionally educated scientist and the layman who always has the kind of mysticism which we could call the pre-scientific "Why?" The nonscientific mind always wants to know too little but also too much. The great break-through, if you allow me this expression, in scientific thought was made when scientists were freed from the search for metaphysical reasons. They began to know how to limit themselves. Phenomena are explained only by other phenomena, which in turn serve to explain still other phenomena. Galileo was the first man, in the time-interval which continues through our day, to have this conception of science.

It is perhaps due mostly to the fact that he invented or, at least, materially realized the telescope. He had enough to do in his lifetime just in looking and in systematizing all he saw. And he did see a great many things. He could confirm, by observation, Copernicus' theory. New stars gave perhaps the first reality to the idea of infinity. He saw that the moon was covered with hills.

But the principal personal work of Galileo remains the foundation of dynamics. Causes are needed for acceleration and not for velocity. Of course only later Newton showed *how* causes of acceleration produce those accelerations. Galileo found that after running down one plane, a ball will run up another to the height of the starting point (friction being neglected). He discovered the law of isochronism of small oscillations of a pendulum and used his studies for the regulation of the clock.

Galileo was the first scientist as we understand the term today. He was also one of the last ones to suffer from religious fanaticism for his astronomical ideas—specifically for his proof of the improved theory of Copernicus. His book, published in Florence in 1632, was denounced by the Inquisition, and at seventy he was obliged to recant, on his knees, these heretical theories of the universe. "E pur si muove!"—"And yet it moves"—were later his famous (and perhaps apocryphal!) words.

The expansion of physical science—in its larger meaning as the science of phenomena—and that of mathematics are so related that the birth of an idea in one of these disciplines follows that of an idea in the other one. Mathematics used by men of experimental knowledge inspired mathematicians and gave them the first elements to be extended and codified. But men with mathematical talent felt also that something completely new had to be invented in mathematics in order to provide a fresh impetus to the physical understanding of the world. The seventeenth century saw the beginning of this double collaboration—collaboration at a distance. It was also in the seventeenth century that the Greek Miracle—love and understanding of pure and disinterested mathematical thinking—found its reincarnation in its almost modern forms.

In connection with pre-Newtonian mathematics, three names have to be cited: Descartes, Fermat, and Pascal.

In his famous book called *Geometry*, Descartes laid down the foundations of analytic geometry. Not only had Descartes by his discovery introduced a new branch of mathematical science, but he had introduced a method of the utmost importance for the whole of mathematics. Analytic geometry made possible the finest study of geometrical figures by analysis, but it also made possible the intuitive study of analysis by means of geometry. From this double point of view it played later on a very important rôle in Newton's discoveries. Descartes insisted upon the fact that the equation of a curve allows the study of all its properties. We shall not speak here about other technical mathematical discoveries of Descartes. Let us only remark that there is not a single exact science or a single technical domain in which Descartes' ideas are not applied.

Fermat was one of the greatest precursors of modern pure mathematics. It could be said that he founded the theory of numbers, one of the most beautiful and one of the least useful parts of mathematics from the point of view of technical applications. It would be wrong to take this assertion in a derogatory sense. It is pure mathematics, mathematics for mathematics' sake, which has made possible the progress of other parts of this science. It is necessary to push pure mathematics very far in order to find in this arsenal of pure knowledge a few truths useful for applications—few, that is, with respect to the whole body of mathematical knowledge. It is because mathematicians have had this pure curiosity that they invented analytic functions, absolute calculus, and matrices, which served afterwards for the foundation of modern theories of electricity, the theory of relativity, and others. But we feel almost sorry to give such reasons for the usefulness of pure mathematics. Mathematicians create pure mathematics as musicians write music, as poets write poems, as philosophers think about space and time. It is true that great physical applications of mathematical theories are made, almost despite the discoverers of these mathematical theories; but one of the noblest characteristics of our civilization is the existence of poets, musicians, and pure mathematicians.

Pascal was the discoverer of the calculus of probabilities. Unlike Fermat, Pascal would not need to apologize since probability is used in physics, biology, and even such practical fields of our life as statistics, economics, and insurance.

With the end of the seventeenth century begins a new era in mankind's thinking. In 1687 Newton had published the first edition of his *Mathematical Principles of Natural Philosophy.* It could be said without exaggeration that this book constitutes the greatest scientific work realized by a single man. It may be said that Newton discovered the Universe, although he gave mostly its mechanical aspects, but at his time the mechanical aspect was the only aspect of the external world.

In establishing the law of gravitation and the equation of dynamics Newton gave the synthesis of the visible world, at any rate of the world visible in the seventeenth and eighteenth centuries. The parts of the Universe invisible even by a powerful telescope became potentially, if not actually, visible by mathematically necessary inferences from Newton's laws.

In separating the two notions, mass and weight, Newton created one of the most important abstractions of the human mind: matter—a concept as fundamental to mechanics as space and time.

The old mathematics was not a sufficient instrument for the new mechanical world. But Newton created the infinitesimal calculus. This great achievement of mathematical thinking was shared also by Leibnitz. Leibnitz' notations seemed, at least at that time, clearer, and were rapidly adopted by continental Europe; but, curiously enough, in modern mechanics it is often preferable to use Newton's original notations. Until very recently, and apart from a few exceptions, infinitesimal calculus and mathematics have been almost synonymous since Newton.

In one word, Newton created a mechanical world, the laws of which were expressed in forms of infinitesimal calculus. The abstraction of the operations used in establishing or in expressing these laws constitutes the new abstract world.

Newton was the creator of the two: the mechanical and abstract worlds.

Newton created modern optics in establishing the law of decomposition of white light by the prism as well as many other fundamental principles of physical optics.

Newton's work brought into being a new spirit. It seemed to his successors that potentially the world was understood. Only details remained to be established. It was sufficient, they thought, from now on to look, to look ably; but the principles were there. Determinism and mechanical Materialism were born. The greatest part of the difference between the thinking of man nowadays and in the seventeenth century is due directly or indirectly to Newton. We do not hesitate to speak about the pre-Newtonian and post-Newtonian man, or at least the pre-Newtonian and post-Newtonian thinker.

The eighteenth century was, as far as astronomy, mathematics, and physics are concerned, rich and original; but astronomy became mostly celestial mechanics, and mathematics the theory of differential equations related to mechanics. Such men as d'Alambert, Legendre, Lagrange, Laplace, and in a large measure Euler, all great mathematicians, lived in Newton's world and their discoveries had one purpose: to continue to refine and to complete (they thought it was possible) the mechanical explanation of the world.

Chemistry was much slower in progressing, and it was only with the discoveries of Lavoisier that this science became free from mysticism and all kinds of semi-philosophical ideas. Lavoisier decomposed water into hydrogen and oxygen, and thus, at the same time, discovered these two elements. By showing the properties of oxygen he was able to reject the old conception of phlogiston—that very special matter with negative weight. He proved that gases have ordinary properties of matter. He proved that matter, even if it changes its forms, does not change in amount.

It is curious to notice how some theories survived from antiquity by passing through the stages mentioned at the beginning of this lecture. Such was the atomic conception which all through the Greek epoch and the Middle Ages attracted metaphysical minds. It lived without any experimental basis: only false causality and not less false finality seemed to justify its existence. Only at the beginning of the nineteenth century did Dalton (1766–1844) give a scientific and experimental foundation to this theory.

We enter into the nineteenth century—the Scientific Age. We have spoken only about certain branches of science, not because the other branches were not cultivated much earlier, but because the discoveries in those scientific disciplines do not seem to have profoundly affected the human mind until the nineteenth century. They constituted either sets of nebulous conceptions, or isolated facts which nobody seemed to recognize as fundamentals of the world to come. Electricity, magnetism, the relationship of both to the theory of light, biology, anthropology, the theory of heredity, modern mathematics, and the new physics were only born, one may say, in the nineteenth century.

But it seems to us that from the point of view of pure science, as great as the discoveries of the nineteenth century may have been, as revolutionary as they were, the Revolution of the Intellect, the almost physiological revolution, was accomplished before. One has the impression that during the Newtonian epoch, and even a century before, the human spirit struggled in cleaning up a mine-field, but once in a free field—free from obscurantism—this spirit could walk fast, although not without great difficulties.

It may be said that during the nineteenth and twentieth centuries human ignorance has been in complete rout. Talent and genius found in their path only technical, professional difficulties; but since means of avoiding them are infinite, infinite also were new discoveries, new theories, and new sciences.

At the same time scientists came systematically and conscientiously in contact with everyday life. Results of discoveries of almost every science were used in improving human life. Engineers familiarized with the newest achievements of scientific research were able to change completely the conditions of men's lives. Since some of my colleagues have given or will give the specific results of these applications, I shall not presume to describe them. My colleagues will do that much better.

Let us only say that since the title of this lecture is "Science in the History of Civilization" and not "The History of Science," and since we have tried to follow the different steps of the influence of science on human intellect until the moment when this intellect became free and full of desires and immense possibilities, we think that we should stop here.

S. MANDELBROJT.